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13. ABSTRACT *(Maximum 200 words)*
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ORIGINAL ARTICLE

Evaluation of the limits to accurate sweat loss prediction during prolonged exercise

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Abstract Sweat prediction equations are often used outside their boundaries to estimate fluid requirements and generate guidance. The limitations associated with these generalized predictions have not been characterized. The purposes of this study were to: (1) evaluate the accuracy of a widely used sweat prediction equation (SHAP) when widening it's boundaries to include cooler environments (2 h) and very prolonged exercise (8 h), (2) determine the independent impact of holding skin temperature constant ($SHAP_{36}$), and (3) describe how adjustments for non-sweat losses (NSL) and clothing saturation dynamics affect prediction accuracy. Water balance was measured in 39 volunteers during 15 trials that included intermittent treadmill walking for 2 h (300–600 W, 15–30°C; $n = 21$) or 8 h (300–420 W, 20–40°C; $n = 18$). Equation accuracy was assessed by comparing actual and predicted sweating rates (211 observations) using least-squares regression. Mean and 95% confidence intervals for group differences were compared against a zone of indifference (±0.125 l/h). Sweating rate variance accounted for by SHAP and $SHAP_{36}$ was always high ($r^2 > 0.70$), while the standard error of the estimate was small and uniform around the line of best fit. SHAP errors were >0.125 l/h during 2 and 8 h of exercise. $SHAP_{36}$ errors were <0.125 l/h for 2 h conditions but were higher at 8 h in three of the six warmest trials. Adjustments for NSL and clothing saturation dynamics help explain SHAP errors at 2 and 8 h, respectively. These results provide a basis for future development of accurate algorithms with broader utility.

Keywords Fluid balance · Hydration · Zone of indifference · Water requirements · Modeling

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Introduction

Estimating human water requirements is an important public health (IOM 2005), sports (Montain et al. 2006), occupational (NIOSH 1986) and military medicine (Departments of the Army and Air Force 2003) problem. The Institute of Medicine (IOM 2005) has identified the "development of capabilities to predict hourly, and daily water requirements based on metabolic rate, climatic conditions, and clothing" as a research priority. Sweat loss is a primary component of determining water requirements for active populations exposed to environmental heat stress. Water losses from sweat increase proportionally with the total thermal load (Davies et al. 1976; Davies 1979), but numerous host (acclimation, fitness, body size, and clothing) and environmental (air temperature, vapor pressure, solar load, and wind) factors can complicate this relationship (IOM 2005). The myriad of complex interactions among variables that influence-sweating rates can make encompassing experiments difficult and impractical, thus prediction models are desirable (Massoud et al. 1998).

The US military employs several empirically derived sweat prediction algorithms to estimate water requirements (Departments of the Army and Air Force 2003; Montain et al. 1999; CASCOM 1999) for a variety of physical activity, clothing, and environmental situations. These sweat prediction algorithms, though not exclusive, are likely the most accurate and widely used (Cheuvront et al. 2002; Departments of the Army and Air Force 2003; Doherty et al. 2006; IOM 2005; Montain et al. 1999; Pandolf et al. 1986; Shapiro et al. 1982, 1995; CASCOM 1999). The exponential equation (SHAP) (Shapiro et al. 1982), embedded within generations of broader empirical sweat prediction models (Berglund and Yokota 2005), resolves the interaction between the requirement for evaporative cooling (E_{req}) and the maximum evaporative capacity of the environment (E_{max}). The SHAP equation, first published in the *European Journal of Applied Physiology* in 1982, was derived from a matrix of laboratory experiments that included a range of environmental conditions (ambient temperature 20–54°C, and relative humidity 10–90%), clothing configurations (insulation or clo = 0.74–1.50), and metabolic intensities (~50–250 W/m^2) of 2 h duration. Actual sweat losses were determined from the change in nude body mass corrected for fluid intake and urine output, but no corrections were made for respiratory or metabolic mass losses [non-sweat losses (NSL)]. This exclusion will over-estimate true sweat losses, especially in cooler environments (Mitchell et al. 1972). In addition, clothing insulation (clo) and evaporative potential (i_m/clo) in SHAP do not account for changes in clothing wettedness over time, which can blunt sweating responses (Chen and Fan 2003; Kakitsuba et al. 1988; Lotens and Havenith 1994). It is therefore clear that the potential impact of these adjustments on equation accuracy deserves attention.

Published water requirement guidance (Departments of the Army and Air Force 2003; IOM 2005; Montain et al. 1999; CASCOM 1999) using SHAP are often for conditions outside original equation boundaries. These include cooler environments and extrapolation to more extended physical activity (12 h) with implications for 24 h fluid needs. SHAP is also sometimes modified from the original method when incorporated into more complex models (Berglund and Yokota 2005; Pandolf et al. 1986) so that an estimated skin temperature is used to compute E_{req} and E_{max}, rather than actual values. The algorithm then requires that only physical activity, environment, and clothing be known (or estimated) to predict sweating rate. A skin temperature of 36°C ($SHAP_{36}$) is most often selected. This is a good approximation under heat stress conditions and in accordance with progenitor papers (Givoni and Goldman 1972) of the SHAP algorithm and the purposes of models that followed (Berglund and Yokota 2005; Pandolf et al. 1986), but its accuracy when generalized across cooler conditions when skin temperatures are lower (Departments of the Army and Air Force 2003; IOM 2005; Montain et al. 1999) remains unknown.

The impact of cooler weather, prolonged physical activity, and high fixed skin temperatures on the accuracy of SHAP predictions for sweat losses and fluid needs requires further investigation. The purposes of this study were to: (1) evaluate the accuracy of a widely used sweat prediction equation (SHAP) when widening its boundaries to include cooler environments (2 h) and very prolonged exercise (8 h), (2) determine the independent impact of holding skin temperature constant ($SHAP_{36}$), and (3) describe how adjustments for NSL and clothing saturation dynamics affect prediction accuracy. Our hypotheses were that (1) SHAP would over-estimate sweating rate in cooler environments due to NSL error and during 8 h exercise due to changes in clothing saturation dynamics, and (2) $SHAP_{36}$ would underestimate sweating rate in cooler environments due to the high skin temperature constant. It is anticipated that these and future experimental studies will provide systematic insight into the development of sweat rate prediction algorithms with broader utility.

Methods

Subjects

Thirty-nine healthy Soldiers participated in this study. Twenty-one volunteers (five women) participated in the 2 h experiments, although not all volunteers completed all nine trials. The number of volunteers completing each trial is provided in Table 1, along with trial letter designations, environment, walking speed, walking grade, work/rest cycles, and other associated data. Descriptive characteristics (mean ± SD) for this group were age 23 ± 4 years, height 174 ± 8 cm, mass 76 ± 11 kg, body surface area (BSA) (Dubois and Dubois 1916) 1.9 ± 0.2 m^2. Eighteen volunteers (one woman) were enrolled in the separate 8 h experiments and the number completing each of the six trials is provided in Table 2 along with other important trial information (as in Table 1). Their characteristics were age 22 ± 4 years, height 177 ± 4 cm, mass 80 ± 13 kg, BSA 2.0 ± 0.2 m^2. All volunteers were provided informational briefings and gave voluntary and informed written consent to participate. Investigators adhered to policies for protection of human subjects as prescribed in Army Regulation 70-25 and US Army Medical Research and Materiel Command Regulation 70-25. The research was conducted in adherence with the provisions of 45 Code of Federal Regulations Part 46.

Table 1 Descriptive data for 2 h experiments

Trial	n	T_a (°C)	rh (%)	Work : rest (min)	Speed (m/s)	Grade (%)	T_{sk} (°C)	Metabolism (W/m^2)	NSL (kg/h)	SR (l/h)
A	15	15	50	2× (50:10)	1.34	5	28.7 ± 0.8	261 ± 19	0.096 ± 0.021	0.307 ± 0.129
B	15	15	50	2× (50:10)	1.56	7	28.8 ± 1.2	348 ± 25	0.160 ± 0.034	0.465 ± 0.159
C	15	20	50	2× (50:10)	1.34	0	31.1 ± 0.8	178 ± 15	0.055 ± 0.011	0.220 ± 0.089
D	19	20	50	2× (50:10)	1.34	5	30.3 ± 1.0	248 ± 23	0.090 ± 0.024	0.397 ± 0.162
E	17	20	50	2× (50:10)	1.56	7	30.2 ± 1.2	349 ± 39	0.154 ± 0.041	0.610 ± 0.191
F	13	25	50	2× (50:10)	1.34	0	31.7 ± 0.6	178 ± 19	0.052 ± 0.013	0.337 ± 0.110
G	10	25	50	2× (50:10)	1.34	5	31.5 ± 0.9	256 ± 22	0.087 ± 0.018	0.482 ± 0.226
H	11	25	50	2× (50:10)	1.56	7	32.1 ± 0.6	348 ± 37	0.138 ± 0.041	0.737 ± 0.244
I	11	30	50	2× (50:10)	1.56	7	33.4 ± 0.7	345 ± 31	0.138 ± 0.035	0.914 ± 0.309

All data are mean ± SD. Wind speed for all trials was 1 m/s

n number of volunteers, T_a air temperature, *rh* relative humidity, T_{sk} mean skin temperature, *NSL* non-sweat loss, i.e., combined respiratory water loss and CO_2–O_2 exchange, *SR* actual measured sweating rate

Table 2 Descriptive data for 8 h experiments

Trial	n	T_a (°C)	Rh (%)	Work : rest (min)	Speed (m/s)	Grade (%)	T_{sk} (°C)	Metabolism (W/m^2)	NSL (kg/h)	SR (l/h)
J	13	40	40	3× (60:20)	1.34	1	36.0 ± 0.6	181 ± 29	0.033 ± 0.009	0.647 ± 0.131
				3× (60:20)	1.12	1				
K	16	35	30	6× (60:20)	1.56	2	34.3 ± 0.5	233 ± 33	0.064 ± 0.018	0.559 ± 0.073
L	15	35	30	3× (60:20)	1.34	1	33.9 ± 0.5	176 ± 15	0.041 ± 0.008	0.452 ± 0.058
				3× (60:20)	1.12	1				
M	15	27	40	6× (60:20)	1.56	2	32.3 ± 0.6	236 ± 24	0.064 ± 0.018	0.397 ± 0.100
N	13	27	40	3× (60:20)	1.34	1	32.7 ± 0.6	173 ± 15	0.040 ± 0.009	0.260 ± 0.057
				3× (60:20)	1.12	1				
O	13	20	50	6× (60:20)	1.56	2	30.6 ± 1.1	230 ± 19	0.063 ± 0.015	0.224 ± 0.085

Abbreviations as in Table 1. All data are means ± SD. Wind speed for all trials was 1 m/s

General protocol and design considerations

All testing was conducted at the Doriot Climatic Chambers facility in Natick, MA. The 2 h study trials were conducted between the months of October and February. Volunteers did not undergo a heat acclimation regimen, but may have been partially heat acclimated by virtue of daily physical activity (as required by Army regulations). To reduce the potential for the acute induction of heat acclimation to confound measurements during the 2 h experiments, the order of trials, as shown in Table 1 (A–I), proceeded from coolest to warmest. Between 24 and 48 h separated each trial.

Eight hour experiments were conducted in the summer months. To prepare volunteers for these prolonged walks in warmer conditions, ten consecutive days of heat acclimation were completed by walking on a treadmill at 1.56 m/s, 4% grade for up to 100 min at 49°C, 20%rh. The environmental and exercise conditions for the 8 h trials and trial order (J–O) are shown in Table 2. Trials were completed from warmest to coolest in order to minimize any impact of heat acclimation decay resulting from the longer recovery time (48–72 h) between trials (for blister care, overuse injuries, etc.).

The metabolic rate and environment combinations were chosen for their realistic applications to public health, occupational, sports, and military communities (Departments of the Army and Air Force 2003; IOM 2005; Montain et al. 1999, 2006; NIOSH 1986; CASCOM 1999). They were also selected for the purposes of (1) extending the lower end of testing conditions used to develop SHAP (2 h experiments) (e.g., only 2 of 30 trials in Shapiro et al. 1982 were below 35°C) and (2) evaluating SHAP performance beyond 2 h in environments similar to those used in the original equation development (8 h experiments). All 2 and 8 h metabolic rate and environment combinations were within the original equation E_{req} and E_{max} domains of validity (Massoud et al. 1998; Shapiro et al. 1982), but the absolute air temperature (2 h trials A and B) or exercise duration (all 8 h trials) were outside the original experimental boundaries so that the limitations of generalizing to these conditions could be characterized and understood.

Measurements and calculations

At the start and conclusion of each trial, nude body mass (kg) was measured on an electronic precision balance scale (Toledo 1D1, Worthington, OH; accuracy ± 20 g). Water from pre-measured bottles was available to drink ad libitum during all trials and a small meal (~500 kcal) was provided during the 8 h experiments. The precise weight of all food, water, and urine was measured on an electronic

scale (Ohaus E1M210, Switzerland; accuracy ± 1 g). The weight of any fecal mass losses was determined via body mass changes pre-to-post void. Actual sweat losses were determined by calculating water balance using a modified Peters–Passmore equation (Consolazio et al. 1963);

$$\text{Sweat loss (kg)} = \Delta \text{ body mass} + (\text{Solids}_{\text{in}} - \text{Solids}_{\text{out}}) + (\text{Fluids}_{\text{in}} - \text{Fluids}_{\text{out}}) - (\text{Gases}_{\text{in}} - \text{Gases}_{\text{out}}),$$

where Δ body mass is the difference in nude body mass pre-to-post exercise, fluids and solids in = water and food, fluids out = urine and respiratory water losses, solids out = fecal mass, and gases represent CO_2–O_2 exchange. Rates of respiratory water and CO_2–O_2 exchange losses were calculated as:

$$\text{Respiratory water loss (g/min)} = 0.019 \times \text{VO}_2(44 - P_a),$$
$$\text{CO}_2 - \text{O}_2 \text{ exchange (g/min)} = \text{VO}_2(R \times p\text{CO}_2 - p\text{O}_2),$$

where VO_2 is oxygen uptake (l/min), P_a is the ambient water vapor pressure (mmHg), R is the respiratory quotient, and pCO_2 and pO_2 are the densities of carbon dioxide (1.96 g/l STPD) and oxygen (1.43 g/l STPD) (Mitchell et al. 1972), respectively. Adjustments for NSL were calculated as the simple sum of respiratory water loss and CO_2–O_2 exchange and total body mass loss calculated as sweat losses plus NSL (Cheuvront et al. 2002). The sum of the entire equation represents actual sweat losses (kg). Sweat volume and mass were considered equivalent (i.e., 1 ml = 1 g) and expressed as a rate (volume per unit time, l/h).

Intermittent treadmill walking was performed for 2 h (300–600 W, 15–30°C) or 8 h (300–420 W, 20–40°C) duration as detailed in Tables 1 and 2. Metabolic rate was measured from VO_2 using indirect calorimetry via Douglas Bags, dry gas meter, and metabolic cart (TrueMax, ParvoMedics, Sandy, Utah). A 90s sample of expired air was collected ~30 min into each hourly exercise bout. Exercise metabolism was taken as the average of these. Metabolism during rest periods was estimated as 1.19 × (body mass/BSA), where body mass is in kg and BSA is m^2 units. This is approximately one metabolic equivalent. Total metabolism was then estimated as a time-weighted average for exercise and rest (Shapiro et al. 1982) (Tables 1, 2).

The actual sweating rates were compared to values calculated using the SHAP sweat prediction equation (Shapiro et al. 1982);

$$\text{Sweat rate (g/m}^2 \times \text{h}^{-1}) = 27.9 \times E_{\text{req}}(E_{\text{max}})^{-0.455},$$

which were then multiplied by BSA/1,000 to obtain sweating rate in l/h units. The components of E_{req} and E_{max} were mathematically adjusted from the original equations (Givoni and Goldman 1972) in order to normalize for actual BSA (rather than an "average man") (Givoni and Goldman 1972) in W/m^2 units. Equation components are;

$$E_{\text{req}} = M - W \pm (R + C) \text{ and } E_{\text{max}} = 14.21 \times i_m/\text{clo} \times (P_{\text{sk}} - P_a).$$

M is metabolic heat production [$M = (0.23[R] + 0.77) \times 5.873 \times VO_2 \times (60/\text{BSA})$] (Gagge and Nishi 1977) where VO_2 (l/min) is weighted as described above and corrected for external work [$W = (0.098 \times \text{body mass} \times G \times v)/\text{BSA}$], where G is treadmill grade (%), and v is walking speed (m/s). $R + C$ is radiative and convective heat flux calculated as [$6.45 \times (T_a–T_{sk})$]/clo (Givoni and Goldman 1972), where T_a is ambient temperature (°C), P_{sk} is the saturated water vapor pressure (mmHg) at mean skin temperature (T_{sk}, °C), calculated as 0.3 ($T_{chest} + T_{forearm}$) + 0.2 ($T_{thigh} + T_{calf}$) (Ramanathan 1964). Clo and i_m/clo values were adjusted for air velocity as described by Givoni and Goldman (1972). The algorithm is the same for both SHAP and $SHAP_{36}$. What differs between them is that $SHAP_{36}$ sets T_{sk} to 36°C and P_{sk} to 44 mmHg (Berglund and Yokota 2005; Givoni and Goldman 1972), while SHAP uses actual (measured) values of T_{sk} (Shapiro et al. 1982). To obtain T_{sk} values for use with SHAP, measured T_{sk} values were averaged for each hour and the grand mean used for calculation (Tables 1, 2). Skin vapor pressures were always assumed to be saturated at a given skin temperature (Gagge and Nishi 1977; Kerslake 1963).

The clothing ensemble worn for all trials was the US Army battle dress uniform (BDU) with field cap, sleeves down, and athletic shoes to reduce blisters. Clothing thermal (clo = 1.08) and vapor resistance (i_m/clo = 0.49) were very similar to one of four clothing ensembles used in developing SHAP (Shapiro et al. 1982) and the one most applicable to the US military (Departments of the Army and Air Force 2003; Montain et al. 1999; CASCOM 1999). The potential for changes in clothing saturation dynamics to affect sweat predictions was a post hoc hypothesis. In the absence of the required measurements, this potential was assessed by simultaneously modeling adjustments in i_m and clo upward and downward, respectively, by 10 and 20% each based upon supporting literature (Chen and Fan 2003; Lotens and Havenith 1994; Nishi and Gagge 1970). The starting ratio i_m/clo (0.49) was therefore increased to 0.60 and 0.74 to determine the theoretical effect of altering clothing wettedness on biophysical predictions of sweating.

Statistical analyses

Predicted sweating rates were compared with measured sweating rates using univariate least-squares regression.

Goodness of fit was determined by application of statistical thresholds for the coefficient of determination ($r^2 \geq 0.70$; very large) (Hopkins 2001) and standard error of the estimate (SEE $\leq$ 0.125 l/h). Uniformity of the prediction error was also examined by scatter plot of the residuals (differences between observed and predicted values) and predicted sweating rates (line of best fit) from the regression analysis.

The practical importance of differences between actual and predicted sweating rates was examined by comparing the mean and 95% confidence intervals for group differences against an a priori zone of indifference (±0.125 l/h). This procedure is a corollary for significance testing (Batterham and Hopkins 2005; Gardner and Altman 2000) and one we have used previously (Cheuvront et al. 2005) which provides insight into the likely range of the true (population) differences (Batterham and Hopkins 2005; Gardner and Altman 2000) while also affording evaluation against an evidentiary standard other than zero (Batterham and Hopkins 2005), similar to equivalence testing (Ebbutt and Frith 1998). Differences beyond ±0.125 l/h between actual and predicted sweating rates were justified as meaningful (Batterham and Hopkins 2005) based upon the logistical implications of a 1.0 l error over an 8-h work day (CASCOM 1999). Sample size estimates (8–15 subjects) for comparing group means to this standard value were made using conventional $\alpha = 0.05$ and $\beta = 0.20$ values for anticipated sweating rates of ~0.50 l/h with sweating rate variability equal to 20–30% of the group mean (Montain et al. 1999; Shapiro et al. 1982, 1995). Simple correlation analysis was also used to describe associations where appropriate. All data are reported as means ± SD except where otherwise indicated.

Results

Descriptive data

Tables 1 and 2 provide descriptive data for all 15 trials (A–O). The total number of observations for 2 and 8 h studies was 126 and 85, respectively. In the 8 h experiments, 59 observations were for the full 8 h, ten observations lasted 6 h, and the remaining 16 observations were 4 h duration due to common ailments inherent to prolonged walking in warm weather (e.g., blisters, heat rash, etc.). All of these trials were considered prolonged intermittent exercise bouts (>2 h) and were therefore analyzed together without distinction. By design, metabolic rate, and environmental temperatures were often higher and lower than those used in the original sweat prediction equation (Shapiro et al. 1982), but mean E_{req} and E_{max} remained within prediction equation parameters of 50–360 and 20–525 W/m^2, respectively. Two exceptions were trials A and C, where mean E_{req} was slightly lower (43–45 W/m^2), but this was considered a probable result of normal human variability since the treadmill settings and environments in these trials were very similar to those previously published for an E_{req} group mean of 52 ± 4 W/m^2 (Shapiro et al. 1982). Mean sweating rates ranged from 0.220 to 0.914 l/h for 2 h experiments and from 0.224 to 0.647 l/h for 8 h experiments. Ad libitum drinking was sufficient to prevent dehydration in excess of 1% initial body mass regardless of the experimental conditions.

Regression analysis (SHAP and SHAP$_{36}$)

The variance in individual sweating rates explained by SHAP and SHAP$_{36}$ methods was above threshold ($r^2 \geq 0.70$) for both 2 h (SHAP $r^2 = 0.81$, SEE = 0.108, SHAP$_{36}$ $r^2 = 0.71$, SEE = 0.126) and 8 h of intermittent exercise (SHAP $r^2 = 0.81$, SEE = 0.095, SHAP$_{36}$ $r^2 = 0.87$, SEE = 0.091) (Fig. 1a, b), but the magnitude of the prediction error (SEE) was near the desired limits of precision (±0.125 l/h) for 2 h data in SHAP$_{36}$. A plot of the residuals against predicted values from the regression analysis (Fig. 2a, b) indicates that the SEE is fairly uniform about the prediction lines for individuals across the range of predicted sweating rates during both 2 and 8 h experiments.

Confidence intervals (SHAP)

In order to test the hypothesis that inclusion of NSL would over-estimate sweat losses in SHAP, an additional plot of SHAP predicted sweat losses against total mass losses (sweat + NSL) was included for comparison. Figure 3 illustrates the differences between predicted sweat rate and actual total mass loss rate (a), as well as differences between predicted sweat rate and the actual sweat rate (b). The means and 95% confidence limits are plotted to indicate the likely range of the true differences. In SHAP trials, the differences between total mass loss and predicted sweating rates were statistically significant (confidence interval does not cross zero) for most of the 2 h trials in Fig. 3a (A, C, D, E, F, and G), but none of the intervals fell entirely outside the a priori zone of indifference. When plotted against actual sweating rate (Fig. 3b), trials B, E, F, and G differences were outside the acceptable indifference zone.

In contrast to the 2 h data, all SHAP (versus total mass loss) and SHAP (versus actual sweat loss) 8 h differences were statistically different from zero (Fig. 3a, b). Whether plotted against total mass loss or actual sweating rate, SHAP differences were unacceptably high (confidence interval does not cross zone of indifference) for all trials (J–O). Since the degree to which SHAP over-predicted sweating rate during 8 h in warm environments (trials J–O) was similar

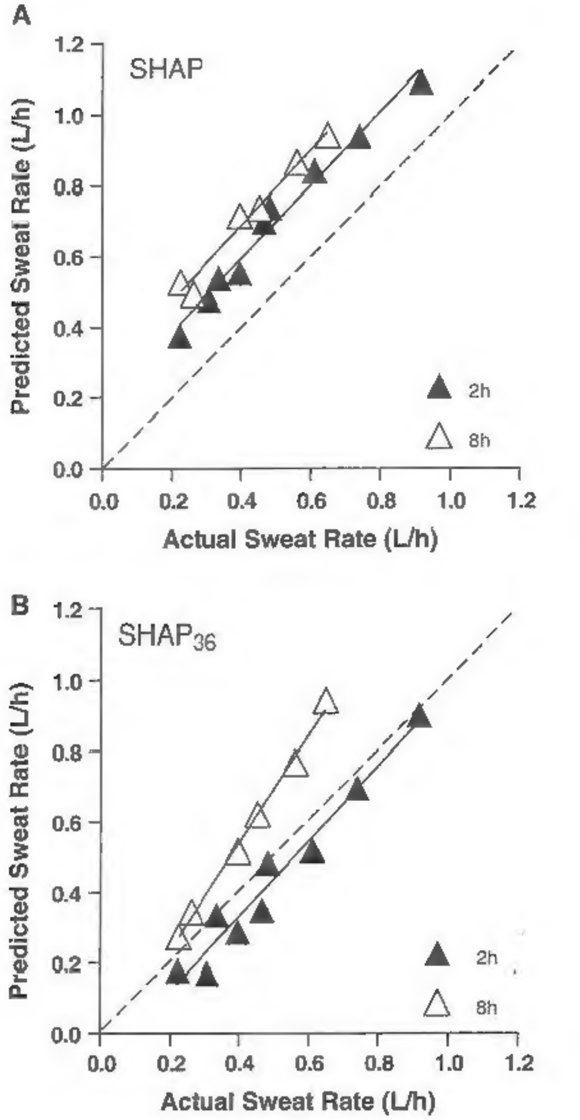

Fig. 1 Regression of predicted (*y*) and actual sweat rate (*x*) during 2 and 8 h of exercise for SHAP (**a**) and $SHAP_{36}$ (**b**). Each point represents the mean of the group for each trial in Tables 1 (A–I) and 2 (J–O). Coefficients of determination and SEE for individual scatter-plots are provided in text. *Dashed line* is unity

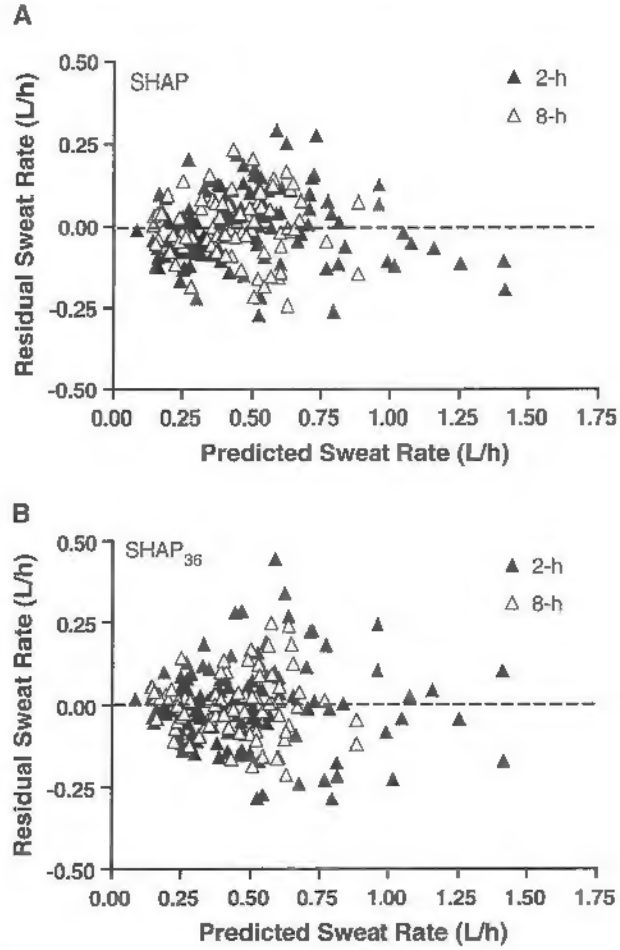

Fig. 2 Plot of residual and predicted sweating rates for the purpose of determining uniformity of error for SHAP (**a**) and $SHAP_{36}$ (**b**). Predicted values are from the line of best-fit regression equations for 2 and 8 h experiments; residuals represent the difference between the predicted and individual observed values

whether expressed relative to total mass loss (Fig. 3a) or actual sweat loss (Fig. 3b), NSL had little impact on 8 h errors. In an effort to better understand SHAP over-predictions during 8 h experiments, the potential impact of changing clothing wettedness was examined. Figure 4a–c illustrates that increasing i_m/clo in the SHAP equation reduces the magnitude of prediction error, which approaches acceptable levels with 20% adjustments (i_m/clo = 0.74).

Confidence intervals ($SHAP_{36}$)

When the only adjustment to SHAP is a fixed T_{sk} of 36°C, 2 h predictions were statistically different for trials A, B, D, and E, but none fell entirely outside the zone of indifference (±0.125 l/h) (Fig. 3c). Differences for $SHAP_{36}$ over 8 h were all statistically different from zero, but only the warmest trials (J, K, and L) were unacceptable when compared against ±0.125 l/h (Fig. 3c). Table 3 illustrates how E_{req} and E_{max} differ as a result of using actual (SHAP) or constant ($SHAP_{36}$) T_{sk} and how this affects sweating rate predictions over 8 h. In cooler environments (20–30°C), holding T_{sk} constant at 36°C results in smaller E_{req} and larger E_{max} values and lower predicted sweating rates when compared to SHAP. As a result, the difference between actual and predicted sweating rates is acceptable for $SHAP_{36}$ in temperate trials (Table 3 and Fig. 3c). But the magnitude of differences increases as a direct function of temperature ($r = 0.91$) (Fig. 5) and both $SHAP_{36}$ and SHAP over-predict sweating by the same amount (Table 3 and Fig. 3b, c) in a hot environment (Trial J) when actual T_{sk} and the 36°C equation constant are the same.

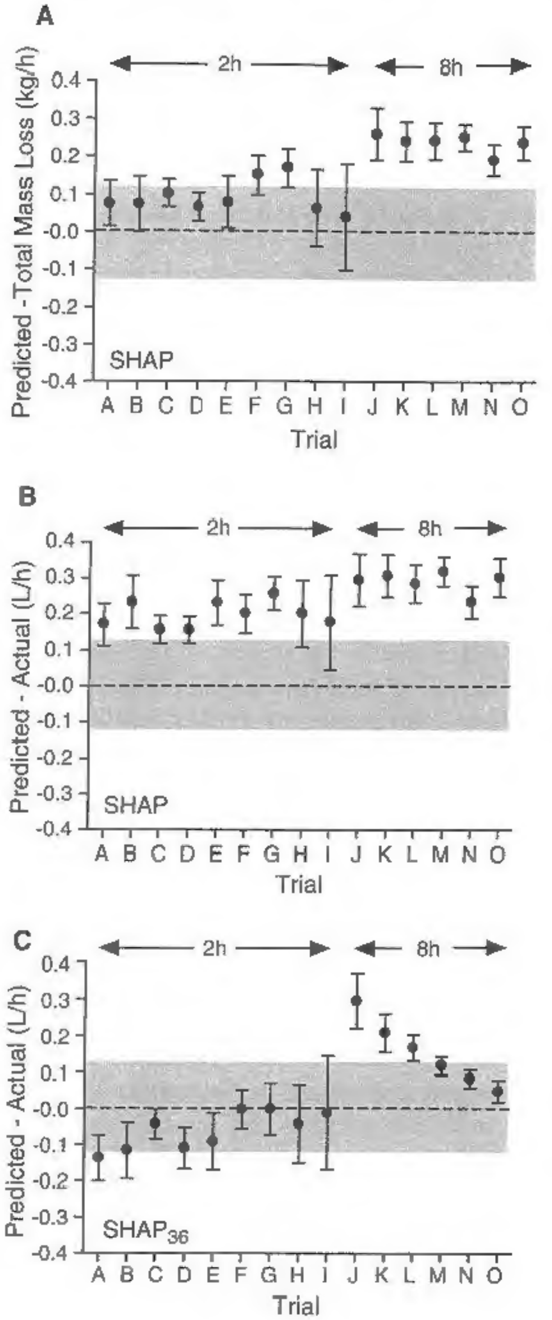

Fig. 3 Differences between predicted sweat rate (SHAP) and actual total mass loss rate (**a**), predicted sweat rate (SHAP) and actual sweat rate (**b**), and predicted sweat rate ($SHAP_{36}$) and actual sweat rate (**c**) during 2 h (A–I) and 8 h (J–O) trials. Data are group (trial) means; *bars* are 95% confidence intervals. *Shaded area* represents zone of indifference (±0.125 l/h) based on the desire to predict sweat losses to within 1 l over an 8-h work day

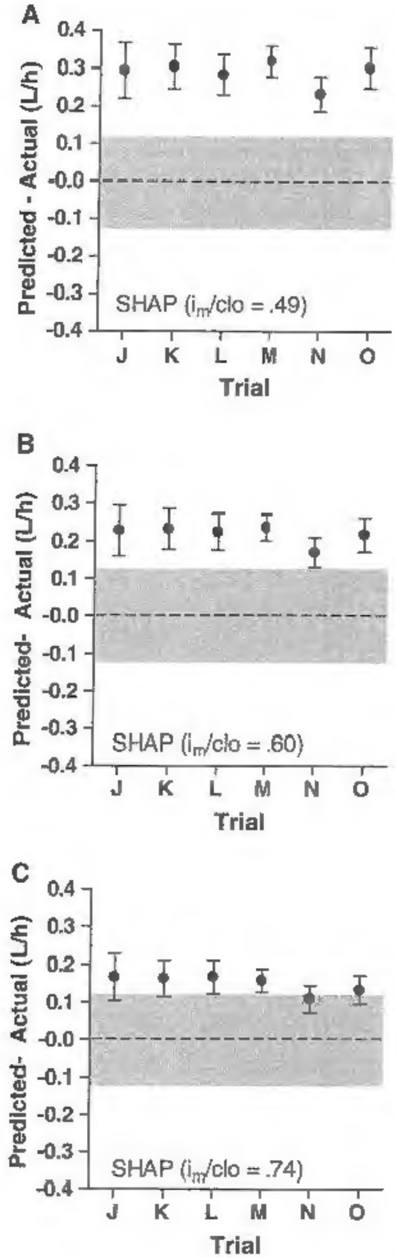

Fig. 4 Differences between predicted and actual sweating rates for 8 h SHAP experiments (trials J–O) when i_m/clo is unchanged (**a**) and after simultaneous adjustments to i_m (increase) and clo (decrease) by 10% (**b**), and 20% (**c**). Data are group (trial) means; *bars* are 95% confidence intervals. *Shaded area* represents zone of indifference (±0.125 l/h) based on the desire to predict sweat losses to within 1 l over an 8-h work day

Discussion

Sweat prediction equations are often employed outside their boundaries to estimate fluid requirements for a variety of conditions, but until now the limitations associated with generalized predictions had not been characterized, nor were any insights available for consideration when developing algorithms with broader utility. The principle findings of this study are that SHAP generally over-estimates sweat losses during 2 h exercise bouts in cool or temperate environments (≤ 30°C), in part because of NSL error. SHAP also over-estimates sweating rates in temperate to hot environments (20–40°C) during 8 h exercise but is

Table 3 Computational behavior of E_{req} and E_{max} within $SHAP_{36}$ and its effect on sweat rate prediction when compared to actual (SHAP) skin temperatures and vapor pressures

	20°C, 50%rh			30°C, 50%rh			40°C, 40%rh		
	E_{req} (W/m^2)	E_{max} (W/m^2)	SR_p (l/h)	E_{req} (W/m^2)	E_{max} (W/m^2)	SR_p (l/h)	E_{req} (W/m^2)	E_{max} (W/m^2)	SR_p (l/h)
SHAP	86	191	0.396	133	188	0.616	186	183	0.871
$SHAP_{36}$	43	292	0.164	115	233	0.481	186	183	0.871
Δ	−43	+101	−0.244	−18	+45	−0.135	0	0	0

Data are modeled for a standard man (70 kg, 1.8 m^2) using a 6× (60:20) work to rest cycle and 1.56 m/s walking speed at 2% grade (metabolic rate = 200 W/m^2). SHAP skin temperatures and vapor pressures (assumed saturated) are means from Tables 1 and 2 for similar environments (trials D, I, and J, respectively). $SHAP_{36}$ represents a constant 36°C skin temperature and 44 mmHg vapor pressure. Δ = $SHAP_{36}$ relative to SHAP. All other abbreviations as described in text

SR_p predicted sweat rate

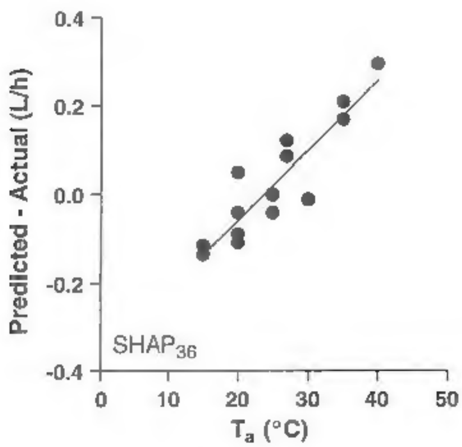

Fig. 5 Relationship between sweat prediction error (y) and air temperature (x) using the $SHAP_{36}$ sweat prediction algorithm that includes T_{sk} and vapor pressure constants. Data are group (trial) means

improved slightly when adjustments are made for expected increased clothing wettedness. Predictions using $SHAP_{36}$ were all acceptable for 2 h trials and at 8 h over-predictions occurred only in the hottest environments (35–40°C).

The variance in actual sweat losses explained by SHAP and $SHAP_{36}$ methods was always high ($r^2 \geq 0.70$) and the SEE small and uniform (Figs. 1, 2) around the line of best fit, making both potentially useful algorithms for the purpose of predicting sweat losses. The likely range of the true population differences between actual and predicted sweating rates in Fig. 3b and c illustrates that SHAP systematically over-estimates sweating rates during 2 h of intermittent exercise due to the inclusion of NSL. Respiratory water and CO_2–O_2 exchange (NSL) represent net losses in body mass which should be accounted for when determining sweat rate from changes in body mass, not unlike corrections for fluid intake and urine output (Cheuvront et al. 2002; Consolazio et al. 1963). Respiratory water losses were not considered to independently impact fluid needs because they are approximately balanced by metabolic water gain (~0.03 g/kJ) (Consolazio et al. 1963; IOM 2005; Mitchell et al. 1972; Pivarnik et al. 1984). While this is true for the experimental conditions tested herein, it does not hold in all situations (e.g., high altitude; Hoyt and Honig 1996). Similarly, so long as CO_2–O_2 exchange is considered, no correction is required for the molecular mass of metabolic water produced by oxidation of substrate (Consolazio et al. 1963; Pivarnik et al. 1984). Thus, sweat loss is of principle importance for determining exercise-fluid needs and failure to correct for NSL (respiratory water and CO_2–O_2 exchange) when calculating sweat losses from changes in body mass can result in a sweat prediction error (Fig. 3a versus b) large enough to be of practical importance (>0.125 l/h). This is especially true in cooler environments where lower water vapor pressures produce larger respiratory water losses (Mitchell et al. 1972) relative to lower sweating rates. This can have important implications for the logistical supply burden associated with military water planning factors (CASCOM 1999).

In contrast, predictions using $SHAP_{36}$ were acceptable for all 2 h trials. This observation is counterintuitive because it would be expected that estimating T_{sk} using a constant value of 36°C would be less accurate than using actual T_{sk} values. It appears that a 36°C T_{sk} constant is often higher than true skin temperatures (Tables 1, 2) for the conditions tested herein. This results in an artificially low E_{req} and high E_{max} calculation (Table 3), which produces acceptable sweating rate predictions (Fig. 3c) when expressed as the algebraic product $27.9 \times E_{req} (E_{max}^{-0.455})$ (Shapiro et al. 1982). The SHAP equation resulted in a consistent over-prediction of sweat rate during warmer 8 h experiments (Fig. 3b) that had little to do with NSL (Fig. 3a). The same was true for $SHAP_{36}$ during the hottest trials when the equation should have performed best (Givoni and Goldman 1972; Pandolf et al. 1986; Shapiro et al. 1982). The question remains why sweat rate predictions worsen when exercise is extended from 2 to 8 h duration?

Figure 4a–c suggests the possibility that increased clothing wettedness and the associated reduction in clothing thermal and vapor resistance could partially explain SHAP over-predictions and improve $SHAP_{36}$ predictions as well during 8 h experiments. As sweat evaporates at the skin surface, the microclimate (area between skin and clothing) can become saturated with water vapor over-time (Kakitsuba et al. 1988). As sweating continues beyond saturation, sweat is absorbed into clothing by capillary action (Chen and Fan 2003; Kakitsuba et al. 1988; Lotens and Havenith 1994). Wetted clothes have lower insulation (Chen and Fan 2003; Kakitsuba et al. 1988; Lotens and Havenith 1994) and higher thermal and permeation efficiency factors (Chen and Fan 2003; Nishi and Gagge 1970), thus increasing sensible heat flux and allowing the maintenance of a constant skin temperature (Kakitsuba et al. 1988; Nishi and Gagge 1970). Although high humidity and wet skin in the clothing microclimate can explain some sweating suppression (Davies et al. 1976; Kakitsuba et al. 1988; Lotens and Havenith 1994; Nadel and Stolwijk 1973), modeling of changes in sensible heat flux at the skin-clothing-environment interface may better explain the observed magnitude of lower sweating rates in wet compared with dry clothing (Lotens and Havenith 1994).

Although the thermal insulation and vapor permeability characteristics for a given clothing ensemble in SHAP (i_m/clo) were done on a wetted copper mannequin to simulate a sweating human (Givoni and Goldman 1972), the degree of clothing wettedness would have been smaller than expected for a body sweating heavily (Chen and Fan 2003; Lotens and Havenith 1994). The precise amount of time necessary for clothing heat transfer properties to reach equilibrium depends on the sweating rate, clothing permeability, and environment, but more than 2 h appears necessary for conditions and clothing similar to those studied herein (Chen and Fan 2003; Kakitsuba et al. 1988; Lotens and Havenith 1994). Some support for this hypothesis can be gleaned from hourly T_{sk} data in trial K, which rose steadily from 33.5 to 35°C over 5 h, after which a discernable plateau occurred for the remaining 3 h of testing (data not shown). Because metabolic rate was held constant, equilibrium sweating, and skin blood flow responses (Stolwijk et al. 1968) may be explained by changes in clothing saturation dynamics (Chen and Fan 2003; Kakitsuba et al. 1988; Lotens and Havenith 1994; Nishi and Gagge 1970). While it is probable that clothing saturation plays a role in the prediction errors observed in the 8 h experiments, other potential contributing factors must also be recognized.

Differences that remain between actual and predicted sweating rates in this study may be explained by fundamental elements related to E_{req}, E_{max}, and the temporal nature of biothermal measurements. The biophysical assumptions of 100% evaporative efficiency and 100% saturated skin vapor pressures are inherent within E_{req} and E_{max}, respectively (Gagge and Nishi 1977; Kerslake 1963), yet these two assumptions do not exist in tandem (Candas et al. 1979a, b; Gagge and Nishi 1977). An error in either assumption could alter predictions substantially. While the measurement of actual efficiency and vapor pressure values is more desirable, this can be difficult, impractical, and would additionally require proper adjustments to related equation constants (e.g., evaporative heat transfer coefficient, h_e) (Kerslake 1963). These parameters, along with simpler measures like T_{sk}, are also limited to average input values that do not account for the temporal changes (Cain and McLellan 1998; McLellan et al. 1996) that occur from exercise, sweating, or clothing saturation dynamics.

Conclusions

This study demonstrated that the generalized use of SHAP systematically over-estimated sweating rates during 2 h exercise bouts in cool or temperate environments while predictions using $SHAP_{36}$ were acceptable for 2 h trials. SHAP also over-estimates sweating rates in warm and hot environments during 8 h exercise, while $SHAP_{36}$ over-predicts only in the hottest environments. Adjustments for NSL and clothing saturation dynamics partially explain SHAP errors at 2 and 8 h, respectively. Like later modifications to SHAP which correct for outdoor solar loads (Shapiro et al. 1995), future generations of sweat prediction equations should consider the importance of NSL, particularly for work in cool environments, and possibly dynamic changes in clothing properties when it is anticipated that sweating will be prolonged. These results should be considered carefully when (1) using SHAP or $SHAP_{36}$ to predict sweat losses or develop fluid intake guidance for civilian and military populations, and (2) developing new prediction equations. The obstacles to accurate sweat prediction presented herein, though non-encompassing, provide a basis for broadening the utility and improving the accuracy of future sweat prediction equations.

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References

Batterham AM, Hopkins WG (2005) Making meaningful inferences about magnitudes. Sportscience 9:6–13

Berglund LG, Yokota M (2005) Comparison of human responses to prototype and standard uniforms using three different human simulation models: HSDA, SCENARIO-J and SIMULINK2NM. USARIEM Technical Report No.: T05-08 (AD A438017)

Cain B, McLellan TM (1998) A model of evaporation from the skin while wearing protective clothing. Eur J Appl Physiol 41:183–193

Candas V, Libert JP, Vogt JJ (1979a) Human skin wettedness and evaporative efficiency of sweating. J Appl Physiol 46:522–528

Candas V, Libert JP, Vogt JJ (1979b) Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency. J Appl Physiol 47:1194–1200

Chen YS, Fan J (2003) Clothing thermal insulation during sweating. Textile Res J 73:152–157

Cheuvront SN, Carter R III, Castellani JW, Sawka MN (2005) Hypohydration impairs endurance exercise performance in temperate but not cold air. J Appl Physiol 99:1972–1976

Cheuvront SN, Haymes EM, Sawka MN (2002) Comparison of sweat loss estimates for women during prolonged high-intensity running. Med Sci Sports Exerc 34:1344–1350

Consolazio FC, Johnson RE, Pecora LJ (1963) The computation of metabolic balances. In: Physiological measurements of metabolic functions in man. McGraw-Hill, New York, pp 313–339

Davies CTM, Brotherhood JR, Zeidifard E (1976) Temperature regulation during exercise with some observations on effects of skin wetting. J Appl Physiol 41:772–776

Davies CTM (1979) Influence of skin temperature on sweating and aerobic performance during severe work. J Appl Physiol 47:770–777

Departments of the Army and Air Force (2003) Heat stress control and heat casualty management. TBMED 507/UFPAM 48-152(I), Government Printing Office, Washington, DC

DuBois D, DuBois EF (1916) Clinical calorimetry: a formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17:863–871

Ebbutt AF, Frith L (1998) Practical issues in equivalence trials. Stat Med 17:1691–1701

Gagge AP, Nishi Y (1977) Heat exchange between the human skin surface and thermal environment. In: Lee DHK, Falk HL, Murphy SD (eds) Handbook of physiology: reactions to environmental agents. American Physiological Society, Bethesda, MD, pp 69–92

Gardner MJ, Altman DG (2000) Confidence intervals rather than P values. In: Altman DG, Machin D, Bryant TN, Gardner MJ (eds) Statistics with confidence, 2nd edn. British Medical Journal, Bristol, pp 15–27

Givoni B, Goldman RF (1972) Predicting rectal temperature response to work, environment, and clothing. J Appl Physiol 32:812–822

Hopkins WG (2001) Summarizing data: simple statistics and effect statistics. In: A new view of statistics. http://www.sportsci.org/resource/ stats/ index.html. Cited 20 Jun 2006

Hoyt RW, Honig A (1996) Environmental influences on body fluid balance during exercise: altitude. In: Buskirk ER, Puhl SM (eds) Body fluid balance: exercise and sport. CRC, New York, pp 183–196

Institute of Medicine (IOM) (2005) Dietary reference intakes for water, potassium, sodium, chloride, and sulfate. National Academy Press, Washington, DC, pp 73–185

Kakitsuba N, Gaul K, Michna H, Mekjavic IB (1988) Dynamic moisture permeation through clothing. Aviat Space Environ Med 59:49–53

Kerslake D McK (1963) Errors arising from the use of mean heat exchange coefficients in the calculation of the heat exchanges of a cylindrical body in a transverse wind. In: Hardy JD (ed) Temperature: its measurement and control in science and industry, vol 3. Reinhold, New York, pp 183–189

Lotens WA, Havenith G (1994) Effects of moisture absorption in clothing on the human heat balance. Ergonomics 38:1092–1113

Massoud TF, Hademenos GJ, Young WL, Gao E, Pile-Spellman J, Vinuela F (1998) Principles and philosophy of modeling in biomedical research. FASEB J 12:275–285

McLellan TM, Pope JI, Cain JB, Cheung SS (1996) Effects of metabolic rate and ambient vapor pressure on heat strain in protective clothing. Eur J Appl Physiol 74:518–527

Mitchell JW, Nadel ER, Stolwijk JA (1972) Respiratory weight losses during exercise. J Appl Physiol 32:474–476

Montain SJ, Cheuvront SN, Sawka MN (2006) Exercise associated hyponatremia: quantitative analysis to understand the aetiology. Br J Sports Med 40:98–105

Montain SJ, Latzka WA, Sawka MN (1999) Fluid replacement recommendations for training in hot weather. Mil Med 164:502–508

Nadel ER, Stolwijk JAJ (1973) Effect of skin wettedness on sweat gland response. J Appl Physiol 35:689–694

National Institute for Occupational Safety and Health (NIOSH) (1986) Criteria for Recommended standard: occupational exposure to hot environments. NIOSH Publication 86-113. US Government Printing Office, Washington, DC

Nishi Y, Gagge AP (1970) Moisture permeation of clothing--a factor governing thermal equilibrium and comfort. ASHRAE Trans 76:137–145

Pandolf KB, Stroschein LA, Drolet LL, Gonzalez RR, Sawka MN (1986) Prediction modeling of physiological responses and human performance in the heat. Comput Biol Med 16:319–329

Pivarnik JM, Leeds EM, Wilkerson JE (1984) Effects of endurance exercise on metabolic water production and plasma volume. J Appl Physiol 56:613–618

Ramanathan NL (1964) A new weighting system for mean surface temperature of the human body. J Appl Physiol 19:531–533

Shapiro Y, Moran D, Epstein Y (1995) Validation and adjustment of the mathematical prediction model for human sweat rate responses to outdoor environmental conditions. Ergonomics 38:981–986

Shapiro Y, Pandolf KB, Goldman RF (1982) Predicting sweat loss response to exercise, environment and clothing. Eur J Appl Physiol 48:83–96

Stolwijk JA, Saltin B, Gagge AP (1968) Physiological factors associated with sweating during exercise. Aerosp Med 39:1101–1105

US Army Combined Arms Support Command (CASCOM) (1999) Water consumption planning factors: a study report. Directorate of Combat Developments, Fort Lee, VA